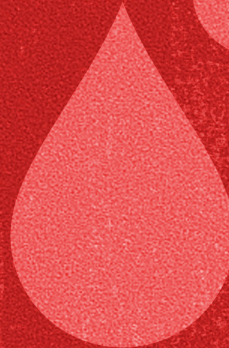
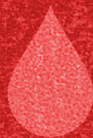
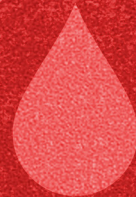
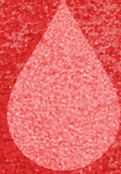


50 BILLION TRILL



Greenland was once lush green tundra and will be so again as its melting ice sheet submerges the world's coastlines. (And, by the way, Antarctica's ice sheet is nearly ten times bigger.)

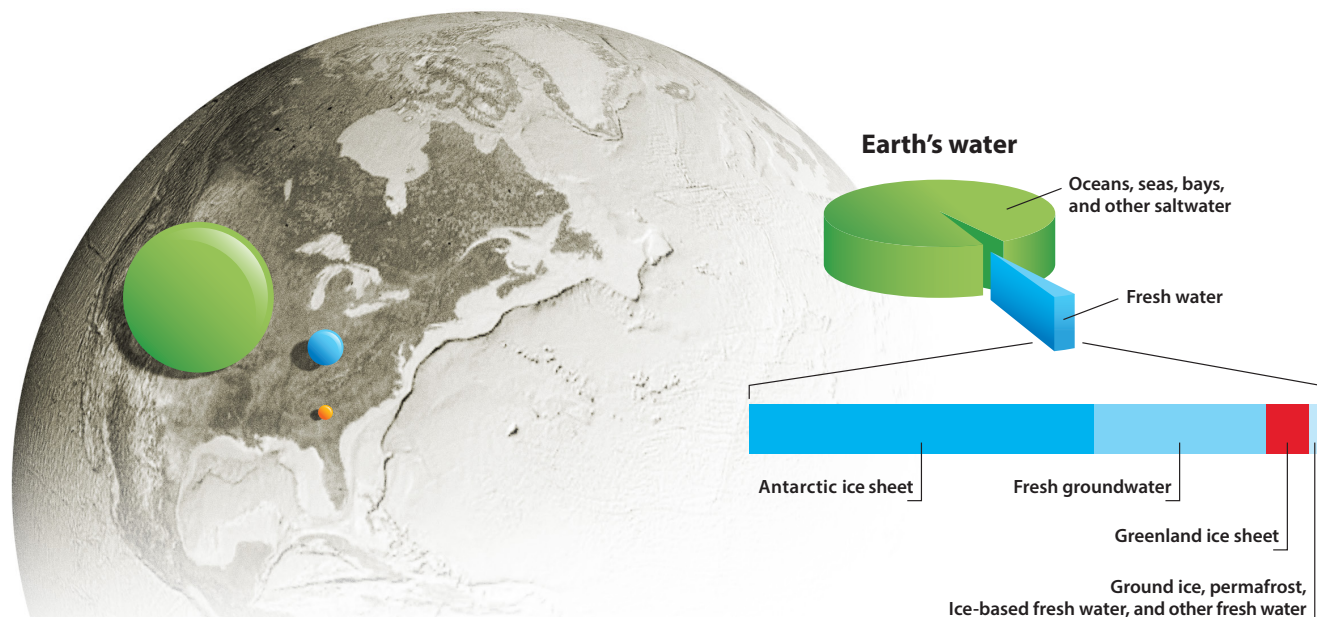
LION DROPS IN THE OCEAN

THIS IS GOING TO SOUND LIKE THE NOW-FAMILIAR STORY about humanity's reckless abuse of the earth and the grave consequences it will have. The story begins with what everybody already knows, that the world is warming, and things are changing in dramatic ways, from droughts to floods to fires to extinctions and, at issue here, rising seas. But this is only barely one of those "unless we do something about it soon" stories. Because while an extremely rapid and comprehensive shift in the world's energy policies could still prevent the worst of it—as predicted in a handful of "let's all adopt renewable energy and buy a Tesla right now" scenarios, as Los Alamos climate scientist Jeremy Fyke calls them—the overwhelming majority of realistic scenarios will result in tremendous ice-sheet loss and sea-level rise.

Fyke tracked a wide range of possible carbon-emission scenarios and their corresponding climate trajectories, and with very few exceptions, they consistently agree about one thing. The massive Greenland ice sheet—accounting for about 8 percent of all the world's fresh water and measuring longer from north to south than the continental United States—will melt into the ocean. The process could take thousands of years, but sometime this century, the human race is expected to make the vast majority of this melt inevitable.

Two ice sheets

In the 1995 movie *Waterworld*, Kevin Costner inhabits a future Earth almost entirely covered in ocean. Realistic? Not to that extreme. There isn't enough water on Earth in any form to submerge that much land. Nonetheless, loss of the Greenland ice sheet would push sea level more than 20 feet higher. That's enough to submerge all or part of virtually every coastal city in the world, plus huge swaths of low-lying land in places like Bangladesh, the Netherlands, the American Gulf Coast, and many others. Florida, for instance, would be a dramatically smaller state. And London, more than 35 miles from the nearest sea, would be under water.



CREDIT: USGS, NSIDC, NASA

All the water on Earth: The large green ball represents the volume of all the water on the planet, if it were pulled from the oceans, ground, and atmosphere. Only 3 percent is fresh water (blue), with about two-thirds of that stored in the Antarctic and Greenland ice sheets, split roughly 90–10 between them. The small orange ball represents all the fresh water accessible for human use, such as groundwater, lakes, and rivers.

Illustration credit: Jack Cook © Woods Hole Oceanographic Institution

Then there's the Antarctic ice sheet to consider. It is nearly ten times larger than Greenland's, and if it were to disappear entirely (a big "if"), that would add another 190 feet of sea-level rise. It goes without saying that the world's coastal cities, in their present locations, would be completely destroyed. Beyond that, the continents would be a lot smaller, with considerably less available land—except in Greenland and Antarctica themselves. Major river deltas, such as the Amazon, Mekong, and Mississippi, would see Great Lake-sized swaths of land completely gone. In numerous regions around the world, interior lands would become coastal; coastal peaks would become islands; and islands would become nothing.

All of this has already begun. According to NASA, the global mean sea level has risen nearly 20 cm (8 inches) since 1870 and is accelerating, having gained almost 9 cm (3.5 inches) just since satellite-based data collection started in 1993. And even though today melting in Greenland and Antarctica together contribute only about a millimeter to sea-level rise each year (plus a few more millimeters from other sources), the future trajectory under business-as-usual carbon emission scenarios is clear: a reversion to an ancient world at a pace unprecedented in the earth's natural history.

"Under a business-as-usual emissions scenario, we're talking about a return to the Cretaceous, like with trees on Antarctica," Fyke says. "And it will stay that way for a long time." That is because it is a lot harder to rebuild the ice sheets than to melt them in the first place. In large sections of Greenland, for example, ice piled higher than 10,000 feet will melt away, lowering the surface elevation to the level of the underlying bedrock, which is close to sea level for much of the

enormous island's interior. With that reduced elevation comes warmer weather, causing precipitation to fall as rain instead of snow that might otherwise rebuild the ice sheet. In other words, average global temperatures may have to drop—not just back to preindustrial levels, but substantially *below* them to ice-age levels—for ice sheets to reappear and bring the global sea level back down.

The ice sheets of Greenland and Antarctica are two very different beasts. In Greenland, ice loss comes primarily from glacial flow and surface melting: some ice flows directly into the ocean, where it melts or forms icebergs, while other ice melts on the surface and then flows as water to the ocean. Antarctica, on the other hand, is isolated from the rest of the world by the cold circumpolar Southern Ocean, making it considerably colder than Greenland and thereby preventing significant surface melting. In addition, much of the Antarctic glacial ice extends great distances over water, rather than breaking off upon leaving the land. Such marine ice shelves, warmed by direct contact with the underlying

PLANET EARTH IS GOING TO HAVE LARGER OCEANS AND SMALLER CONTINENTS

sea, are the primary locations for Antarctic ice loss. In other words, while Greenland is melting primarily because the air is getting warmer, Antarctica is melting primarily because the ocean is getting warmer. The physics of the two processes is quite different, with Greenland's process considerably better understood at present—in no small part because, as Fyke says, accessing sub-shelf cavities in Antarctica is "nearly as difficult as sending a spaceship to another planet."

Much of Fyke's recent work has focused on Greenland, which is currently losing ice about twice as fast as Antarctica. Most of Fyke's colleagues at Los Alamos, however, are turning

their attention to improving models of Antarctica. It's much harder work because there are bigger unknowns with Antarctica than there are with Greenland. But there's also a lot more ice to worry about, so those unknowns translate into much greater uncertainty in future sea-level rise.

Melting ice and boiling beaches

Fyke and his colleagues use sophisticated computer simulations to study the coupling between ice sheets and climate, as is necessary to correctly capture the effect each has on the other. Warmer air leads to smaller ice sheets, certainly, but conversely, when a gigantic mountain of ice goes away, global air-circulation patterns change in ways that can't be ignored. Without such couplings properly taken into account, climate model predictions go increasingly awry as they project further into the future.

"There's a tremendous amount of inertia in the coupled climate system," Fyke says. "Due to feedbacks, in certain cases it's like a ball kicked over the lip of a hill. Once it is sufficiently set in motion, it will continue rolling for a long time." And therein lies the crux of the issue that occupies so much of Fyke's professional attention. Since rapidly accumulating carbon emissions over the coming decades will determine the long-term temperature for many thousands of years to come—and since ice sheets lose elevation more easily than they regain it—how long will it be until the Greenland ice sheet, already melting rapidly, reaches a point of no return? Using an established middle-of-the-road emissions scenario (which humanity is significantly outpacing so far), he estimates that in about 50 years or less, cumulative carbon emissions will drive the ice sheet to a point of no return for long-term deglaciation towards a nearly ice-free state.

This is an extraordinarily impactful near-term threshold, to be sure, but melting ice is hardly the only far-reaching planetary change looming on the horizon. For instance, farther down the cumulative-emissions road lies a different kind

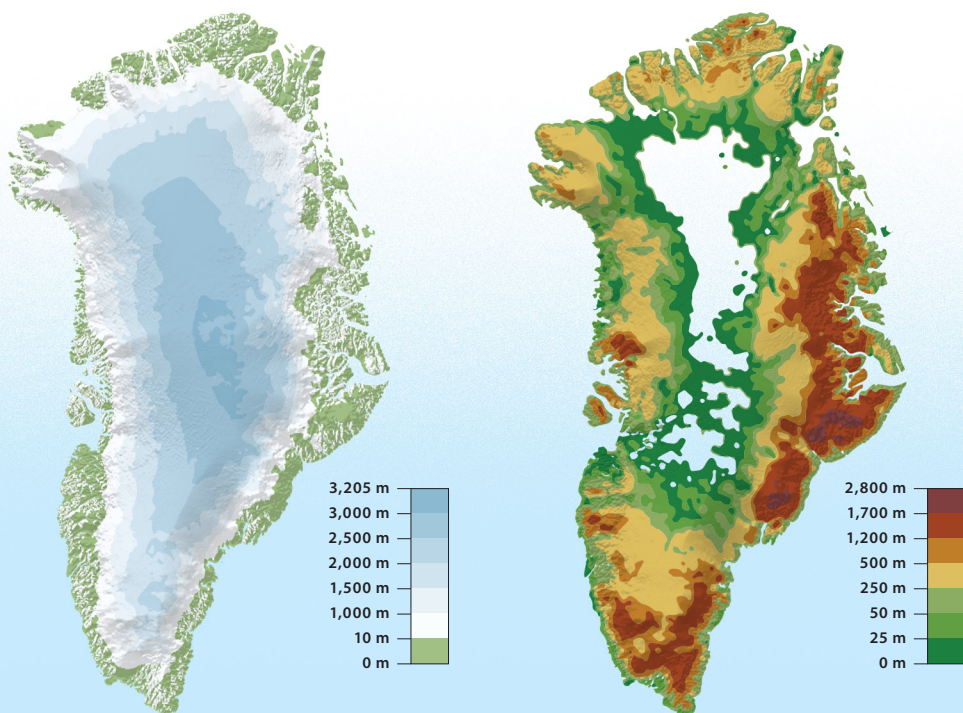
of threshold—not for polar ice sheets or coastal cities, but for human survivability on tropical lands. A cutoff value of something known as the wet-bulb temperature, which blends normal temperature and humidity, marks the highest temperature that mammal physiology can handle by evaporative cooling, such as sweating. Above that wet-bulb temperature, humans and other mammals—even naked, in the shade, in front of a fan—gain more heat from the air than they lose and ultimately experience fatal overheating.

WE COULD BE GOING BACK TO THE CRETACEOUS—IMAGINE ANTARCTICA WITH TREES

Climate models predict that within a few hundred years of ongoing business-as-usual emissions, the wet-bulb temperature throughout much of the tropics will be too high to support human life. Clear limits on how much heat and humidity mammals can tolerate—"probably from experiments on thousands of rats," Fyke says—indicate that people exposed to those conditions would overheat and die from heat stress, rendering much, and perhaps most, of the tropics (in addition to the submerged coastlines) literally uninhabitable.

It's the money

Fyke doesn't just work with complicated and computationally demanding climate models. He has also designed an energy-economy model that calculates rates of fossil-fuel discovery, extraction, and consumption based on a large number of factors that change over time. These factors include, for example, population growth and average per-capita energy use, the relative prices of fossil and non-fossil energy, and the



Greenland's ice sheet covers more than 80 percent of the island and reaches a maximum thickness of 3200 meters (10,500 feet). The current elevation profile of the underlying bedrock suggests that upon complete melting, Greenland would accommodate a large inland sea, similar to the Mediterranean. However, most or all of this land would rise above sea level without the weight of the overlying ice sheet.

CREDIT: (left) Eric Gaba, (right) NOAA

rate at which society transitions to non-fossil energy once its price dips below that of fossil energy. (This latter transition will be gradual because existing fossil-fuel infrastructure cannot be replaced with non-fossil infrastructure overnight.)

Ultimately, the model predicts cumulative carbon emissions, and a critical part of the analysis involves the key factors that affect the relative pricing of fossil and non-fossil energy. For example, how large are the world's existing, easily accessible fossil-fuel reserves? What carbon tax might be applied to fossil energy use? How rapidly will non-fossil resources drop in price with economies of scale as they are more widely deployed? How long will it take to shift to non-fossil energy sources once the two prices reach parity?

For each of these and other uncertain parameters in Fyke's model, based on expert opinion where available, he assigns a range of possible values and an accompanying probability distribution using a standard bell curve, or "normal distribution," to capture the greater likelihood of central values but also the possibility of extreme values. In total, he combines 17 such parameter distributions. Because the parameters are probabilistic, each is chosen randomly in accordance with the specified probability distributions in a way that varies from one simulation to the next and, when taken together, describes a wide swath of possible future scenarios.

Once less than 5 percent of total energy demand in any given run of the simulation is found to be supplied by fossil-fuel sources, which Fyke considers a sufficiently complete transition to non-fossil energies, he tallies the cumulative carbon emitted by that time. He feeds that figure into a mathematical relationship known as the Transient Climate Response to Emissions (TCRE), which relates cumulative carbon emissions to the resulting global average rise in surface temperature that is reached—and largely maintained for centuries after all carbon emissions have stopped. The TCRE relationship, remarkably simple in its linearity, was discovered recently by climate scientists using complex numerical carbon-cycle-climate models. It is derived from simulations performed at various climate-modeling centers

and is itself a source of uncertainty, carrying with it another probability distribution in Fyke's analysis.

Importantly, several poorly understood climate processes, such as the release of methane (a powerful greenhouse gas) from thawing permafrost, are not yet included in the simulations that generated the TCRE. As a result, the range of values that describe the warming response to carbon emissions in Fyke's work is potentially too low. These omissions mean that his results are probably a conservative lower bound on actual temperature change in response to emissions.

Despite the significant uncertainties, Fyke was able to validate his simulation with a hind-cast. He set it to start in 1980, using parameter values and probability distributions appropriate to what was known then, and allowed it to predict energy consumption and carbon emissions from that point until 2012, a time period with good data for comparison. Then, upon demonstrating success with past data, he set simulations to predict forward into the future.

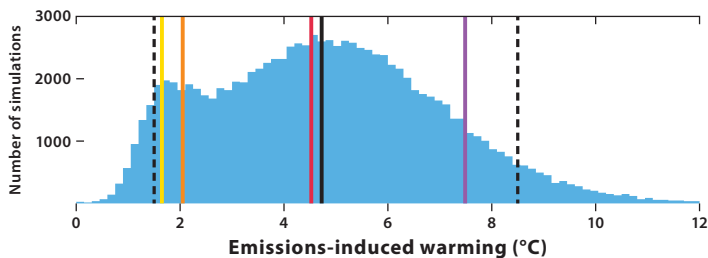
Bad news first

To fully explore all possible future scenarios, Fyke ran 100,000 forward-predictive simulations. Each run yielded a different outcome due to the inherently probabilistic nature of the experiment, but with so many runs, a coherent picture emerged to reveal which planetary warming outcomes are most likely. In fact, the likelihood of a given level of temperature rise could be measured by how many runs within the ensemble produced that result.

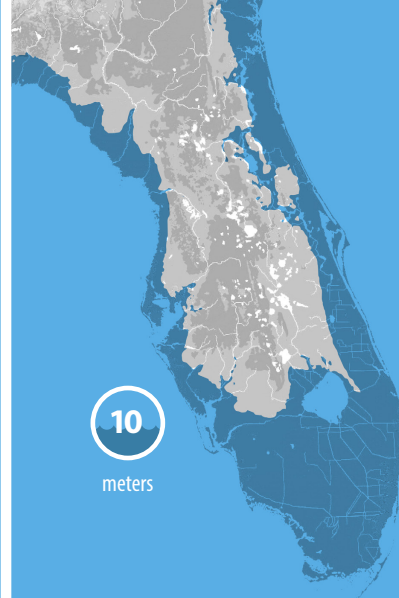
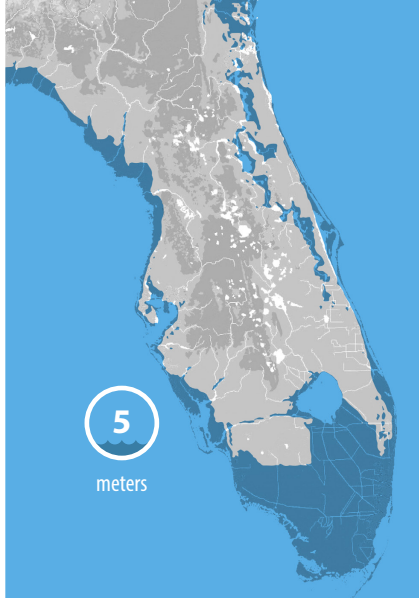
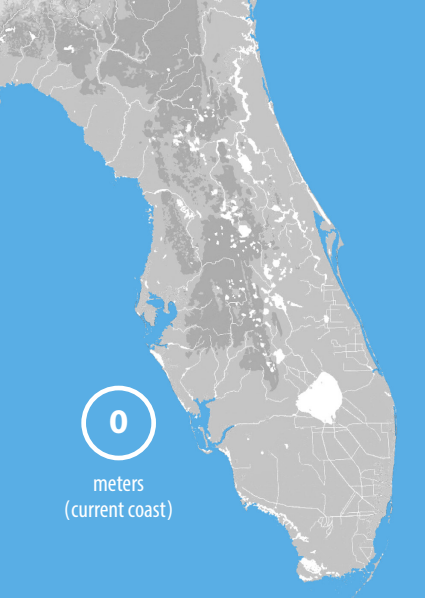
THE MODEL IS CONSERVATIVE, MEANING THE REAL RESULTS COULD BE MORE EXTREME

In the average result across the full distribution of simulation outcomes, the global surface temperature increase due to human-induced climate change—already at 0.9°C (1.6°F)—is slated to peak at 4.7°C (8.5°F). That's well beyond several key climate thresholds, such as the oft-quoted allowable limit for temperature rise of 2°C, at which scientists predict extreme and widespread wildfires, crop failures, droughts, and heat waves, with the hottest days of the year in much of North America, including New York and Washington, D.C., as much as 8°C (14°F) hotter than before. At about 4.5°C, global vegetation is expected to max out its ability to soak up additional carbon dioxide from the atmosphere. And what about the calculated threshold for the stability of the Greenland ice sheet and the 20-plus feet of sea-level rise it's currently holding back? That's only 1.6°C. Only about 6 percent of Fyke's simulation outcomes remain below this level; the other 94 percent all cross it.

The threshold for making many tropical regions uninhabitable to humans and other mammals is estimated to be 7.5°C. About 12 percent of Fyke's simulations cross this temperature



Of 100,000 supercomputer runs of a coupled ice and climate simulation using a probabilistic evaluation of 17 key unknown parameters—such as remaining fossil fuel resources, any future carbon tax, and the rate at which non-fossil-fuel energy prices drop over time—global temperature peaks between 1.4 and 8.5°C above preindustrial levels (dashed lines, indicating the 5th and 95th percentile results). The mean rise is 4.7°C (solid black line). Approximate threshold values for key climate tipping points are shown with colored lines: loss of the Greenland ice sheet (yellow), 2°C standard target level (orange), loss of additional carbon-dioxide uptake by vegetation (red), and heat stress rendering tropical regions uninhabitable to humans and other mammals (purple).



Within the United States, Florida and the Gulf Coast are particularly vulnerable to sea-level rise. This sequence shows much of Florida as it is today (left) and as it will be after a sea-level rise of 5 meters (16 feet, or about 70 percent of the Greenland ice sheet, center) and 10 meters (33 feet, representing all of Greenland and much of Western Antarctica, right). Even just a little over half a meter (2 feet) of water would submerge much of Miami and the South Coast of the state.

CREDIT: Climate Central

threshold. However, as with many climate thresholds, this one is fuzzy; before the world hits 7.5°C, some isolated parts of the tropics will likely have already passed the wet-bulb temperature threshold for habitability.

The silver lining of Fyke's study, depending on one's point of view, comes from the fact that it targets no particular public policy initiative or intergovernmental collaboration to curb emissions. Rather, it is intended to simulate all possibilities, all the way from a continuation of the previous century's reliance on fossil energy to a rapid transition to a clean-energy world. The huge range of climate responses the model produces under these diverse scenarios clearly demonstrates that if governments, businesses, and citizens wanted to, they could greatly influence the range of future warming. For example, they could almost certainly save the tropics from lethal warmth and maybe even come in below the 2°C cutoff. Saving the Greenland ice sheet remains a stretch, as a significant part of it melting and raising sea levels seems all but inevitable based on Fyke's simulations. But preventing other undesirable outcomes remains possible, and the simulation results even reveal how to go about it.

"We performed a multiple linear regression of normalized input parameters and were able to identify which policy levers make the most difference in heading off climate change in the model," says Fyke. He notes that the biggest factor within human control turns out to be the price of non-fossil energy. "If governments subsidized non-fossil energy—or conversely, increasingly taxed carbon emissions in a politically acceptable and revenue-neutral way—they could ensure we stay on the lower end of the range of possible warming outcomes." Other climate policy researchers using completely different methods have similarly concluded that such subsidies or taxes would provide an efficient mechanism for minimizing future climate change—providing useful corroboration for Fyke's novel model.

Keep calm and paddle on

All evidence from Fyke's research indicates that government, private sector, and societal action to mitigate climate change would have to be sweeping to save much of the Greenland ice sheet, because its cumulative carbon-based

tipping point is so close. And if most or all of Greenland goes, a comparable volume (or more) from Antarctica could add its meltwater to the ocean as well. That means the likely outcome in the centuries and millennia to come, Fyke concludes, is a greatly changed world: huge swaths of coastal land lost, huge swaths of Greenland and other arctic regions made temperate and accessible, and a wide basket of fundamental changes and challenges everywhere else. Future generations will live on a very different planet. But in a profound twist, exactly how different will be determined mainly by the current generation.

In the meantime, Fyke and his Los Alamos colleagues are turning their attention to the largest question mark in their coupled ice and climate models, Antarctica. Its ice sheet, ice shelves, saltwater sea ice, and rising Southern ocean temperatures all couple to the broader climate system, sharing numerous complex feedbacks yet to be spelled out in detail. Los Alamos scientists and their supercomputers are working to understand the interplay of changes facing the planet. So the answers are coming, whether or not the solutions are.

—Craig Tyler

More climate science at Los Alamos

- **Climate and ocean modeling**
<http://www.lanl.gov/discover/news-release-archive/2014/September/09.25-climate-earth-system-project.php>
<http://www.lanl.gov/newsroom/picture-of-the-week/pic-week-9.php>
- **Atmospheric monitoring**
<http://www.lanl.gov/discover/publications/1663/2014-august/sampling-sky.php>
<http://www.lanl.gov/newsroom/picture-of-the-week/pic-week-38.php>
- **Forest drought and wildfire**
<http://www.lanl.gov/discover/news-release-archive/2015/December/12.21-disappearance-of-conifers-due-to-climate-change.php>
<http://www.lanl.gov/discover/news-stories-archive/2015/March/climate-and-wildfires.php>
- **Glacial lubrication from meltwater**
<http://www.lanl.gov/discover/publications/1663/2013-nov/moulin-bleu.php>